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Cosmic Ray induced ionization in the upper, middle and lower atmosphere simulated with CORSIKA code

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Abstract: Physical model for calculation cosmic ray induced ionization in the atmosphere is presented. The model is based on Monte Carlo simulation with CORSIKA 6.52 code using FLUKA and QGSJET hadronic interaction subroutines. On the basis of the simulation results the ion pair production in the atmosphere and the impact of the different shower components, precisely the electromagnetic, muon and hadronic is estimated. The simulations are carried out with realistic atmospheric model and following steep spectrum. The model is applicable in the entire atmosphere from the ground up to the upper atmosphere and ionosphere. A comparison with direct rocket measurements is provided. The validation of the proposed model is confirmed.

Introduction

The galactic cosmic rays create the ionization in the stratosphere and troposphere and also in the independent ionosphere layer at altitudes 50-80 km in the D region [1]. First Van Allen [2] received cosmic ray produced ionization in the atmosphere on the basis of V2 rocket sounding measurements

Obviously the ionization profiles are connected with energy deposit of the EAS particles. In this work we use the ionization yield function Y which is defined according [3]

$$Y(x,E) = \Delta E(x,E)\frac{1}{\Delta x}\cdot\frac{1}{E_{ion}}\cdot\Omega \qquad (1)$$

where ΔE is the deposited energy in layer Δx in the atmosphere and Ω is a geometry factor, integration over the solid angle with zenith of 70 degrees. Therefore the ion pair production q by cosmic rays following steep spectrum may be calculated according the formula:

$$q(h,\lambda_m) = \int_{E_0}^{\infty} D(E,\lambda_m)Y(h,E)\cdot\rho(h)dE \quad (2)$$

where $D(E,\lambda_m)$ is the differential primary cosmic ray spectrum at given geomagnetic latitude λ_m, Y is the yield function, $\rho(h)$ is the atmospheric density (g.cm^{-3}).

It is possible to estimate the energy deposit by different primaries on the basis of Monte Carlo technique, precisely using simulations with CORSIKA code [4].

Simulations and Results

As was mentioned above the energy deposit in the atmosphere is obtained on the basis of simulations carried out with CORSIKA code. The recent version CORSIKA 6.52 code [4] with corresponding hadronic interaction models FLUKA 2006 [5] and QGSJET II [6] is used for the simulations. The FLUKA 2006 is used for simulation of hadronic interactions below 80 GeV/nucleon and QGSJET II for hadronic interactions above 80 GeV/nucleon respectively. The atmosphere is divided in 103 steps of 10 g/cm^2, which assures good precision. The used statistics is 5000 events per energy point for given particle. The simulated energy points are 1 GeV, 10 GeV, 100 GeV and 1 TeV kinetic energy of the primary particle – protons. During the simulations the SLANT version of the code is used [7] with CURVED version [8] with realistic curved atmospheric model according the US Standard Atmosphere. This permits to simulate precisely the longitudinal development of the shower and thus cosmic ray induced ionization in the atmosphere. The standard version of the CORSIKA code is designed for simulations of EAS with practically vertical incidence. In the energy range around the "knee" and for EAS with very inclined zenith angle (θ>60 degrees) the majority of the shower particles are absorbed in the atmosphere.

The ionization yield function *Y* which gives the number of ion pairs, produced in 1 g of the ambient air at a given atmospheric depth by one particle of the primary cosmic ray radiation with the given kinetic energy per nucleon (3) is obtained with CORSIKA 6.52 code. In (3) for *Y* is used E_{ion}=35 eV, which is the energy needed for production of one ion pair [9]. The results are presented in Fig. 1-4.

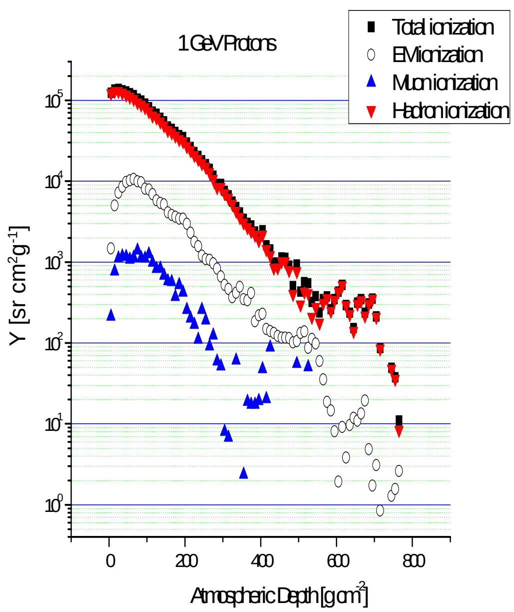

Figure 1: Ionization yield function *Y* for Proton induced EAS with 1GeVenergy

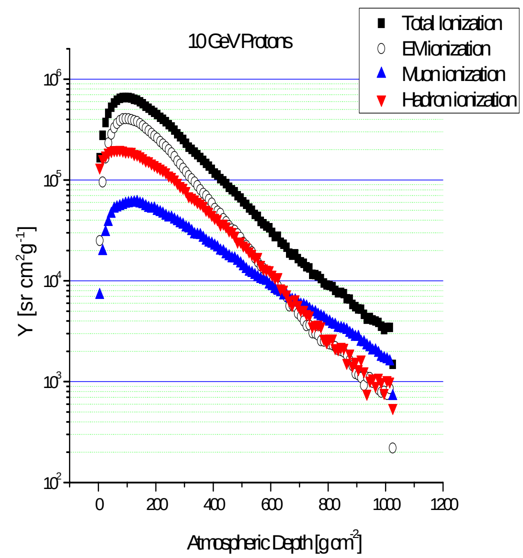

Figure 2: Ionization yield function *Y* for Proton induced EAS with 10GeVenergy

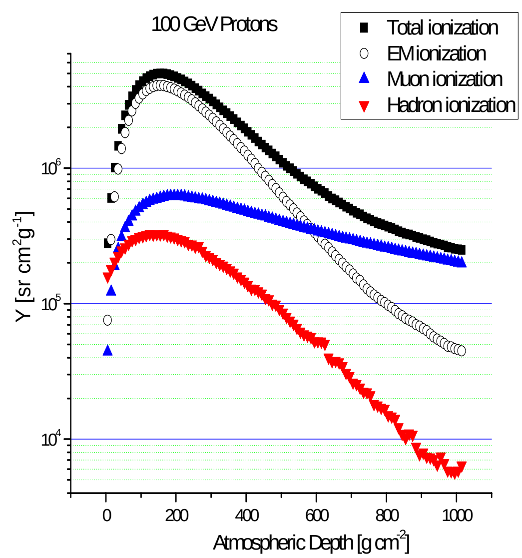

Figure 3: Ionization yield function *Y* for Proton induced EAS with 100 GeV energy

One can see the variation of the contribution of the different components as a function of the energy of the incident particle. In the low energy range the dominant component for total ionization is the hadronic. Increasing the energy as was expected the ionization increases. At the same time the contribution of the different components changes as a function of the energy of the incident particle and the atmospheric depth. With the energy increases then role of the electromagnetic component which in practice dominates in the high energy range above several tens of GeV. Moreover in the high atmosphere at observation levels above 600 g/cm^2, which are in practice near to shower maximum, the contribution of the EM component is more important comparing to other components. At lower atmosphere the ionization is due essentially to muon component. In the range of very high energies, around TeV in practice the EM component determines the ionization.

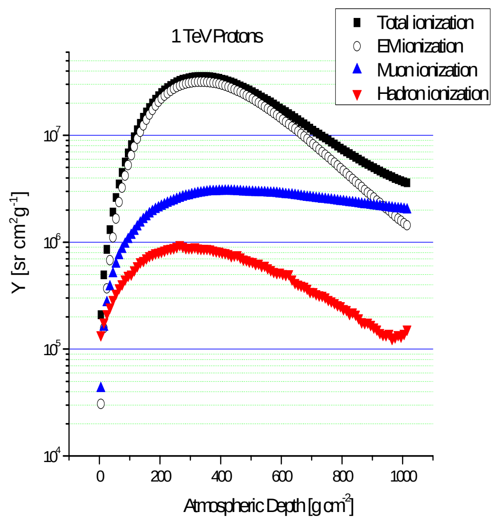

Figure 4: Ionization yield function Y for Proton induced EAS with 1 TeV energy

The results are presented in Fig. 5 for four geomagnetic latitudes λ_m= 0°, 30°, 41° and 55°. The corresponding geomagnetic cut-off rigidities R_c are 14.9, 9, 5 and 1.5 GV. The corresponding cut-off energies for the protons are 15, 9, 5 and 1 GeV. We can express R_c by means of the first approximation

$$R_c \approx 1.9\, M \cos^4 \lambda_m = 14.9 \cos^4 \lambda_m \qquad (4)$$

This is the well known Störmer's approximation. The vertical geomagnetic cut-off is yielded in GV, M is the dipole moment of the geomagnetic field expressed in 10^{22} Am^2. The present value of M = 7.8×10^{22} Am^2 corresponds to $R_c \approx 14.9$ GV at the geomagnetic equator. In this case the simulations are carried out following steep spectrum.

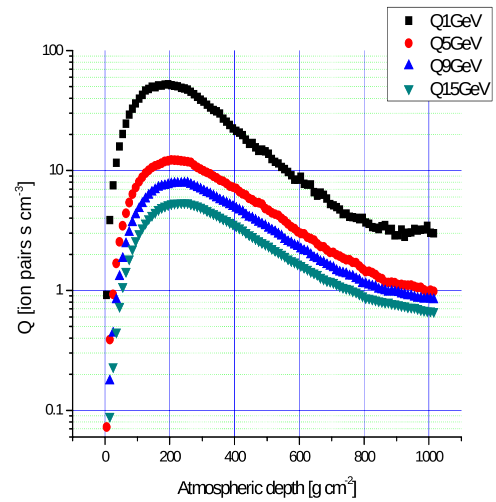

Figure 5: Ion pairs for Proton induced showers for 1, 5, 9 and 15 GV cut offs

In addition an experimental comparison is carried out Fig. 6. The observed difference is due essentially on the not taking into account the heavy nuclei contribution.

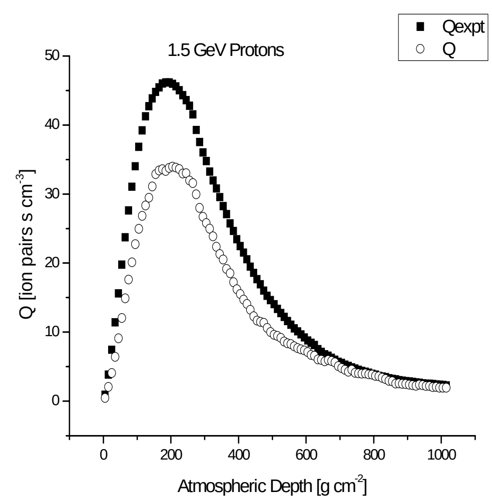

Figure 6: Comparison between simulated and experimental ionization profiles for 1.5 GV

Conclusion

In this work is presented new model for calculation of the ionization of primary cosmic rays into the Earth atmosphere. Using CORSIKA code version 6.52, with corresponding hadronic interaction models FLUKA 2006 and QGSJET II, the deposited energy, respectively the yield function Y, by different components of EAS initiated by primary protons is obtained in wide energy range [10]. The results allowed us to estimate the ion pair production in different regions of the Earth, precisely in equatorial, middle and polar latitudes. The obtained results in this work give a good basis for study of ozone production in Pfotzer maximum and solar-terrestrial influences and space weather. This study is a good basis for present and future studies of the space weather at BEO Moussala.

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